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TITLE: STATUS OF STEADY-STATE IRRADIATION TESTING OF MIXED-CARBIDE FUEL DESIGNS

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STATUS OF STEADY-STATE IRRADIATION TESTING OF MIXED-CARBIDE FUEL DESIGNS

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I. INTRODUCTION

During the period 1957-1974, the irradiation testing of advanced LMFBR fuels in the United States investigated many concepts and materials under widely ranging operating conditions. Several very promising designs emerged, and work in advanced fuel pin design and development since 1974 has come to fruition in the very successful irradiation performance of mixed-carbide fuel pins in the EBR-II. A principal objective of the national program has been to develop advanced LMFBR fuel systems having breeding ratios of at least 1.3, doubling times of 15 years or less, and peak burnup capabilities of 150 MWd/kg. Peak burnups of 190 MWD/kg have been achieved, and calculations show that carbide fuels can easily meet the breeding ratio and doubling time goals. Carbide fuel offers considerable potential for excellent LMFBR performance because of its high metal atom density and high thermal conductivity. The latter permits larger fuel pins, resulting in fewer total pins and hence less cladding and pin spacer material in the core. Decreasing the dilution of the core with inert material results in spectral hardening and thereby in decreased parasitic capture of neutrons in the remaining inert diluents, leading to significant improvements in breeding ratio and doubling time over those obtainable with oxide fuel.

II. MAJOR VARIABLES IN CARBIDE TESTS

The carbide fuel tests in the EBR-II have included many variables. Pins with outside diameters of 7.87 mm and 9.40 mm were tested. These diameters were chosen so that 127 of the 7.87 o.d. pins or 91 of the 9.40 mm o.d. pins fit a standard FFTF driver assembly duct. The fuel-cladding thermal bond was helium in over half of the pins and was sodium in the rest. The four cladding alloys tested were Type 316 stainless steel, Nimonic PE-16, and the advanced alloys D9 and D21. In both helium and sodium bonded pin types, variations in the fuel smeared density were included, being accomplished with variations in both the fuel pellet density and the fuel-cladding gap in the helium-bonded pins and with differences in the gap in the sodium-bonded pins. In the latter, the fuel pellet density was > 98% T.D. in all pins. A fuel shroud tube, a perforated metal tube, has been used to contain the column of fuel pellets in a cylindrical geometry in sodium-bonded pins. Shroud tubes were included in most of the sodium-bonded pins, and they performed well. In some of the pins in three of the tests, the shroud tubes were omitted, and these pins also performed well. Peak linear power and peak cladding temperature were also variables. Some of the tests simulated the conditions of power, temperature, and burnup anticipated at the core midplane in the FFTF, and other tests simulated the conditions anticipated at the top of the core. Tests at nominal temperatures and also at 2σ hot cladding temperatures have been conducted. Most of the test assemblies had wrapped-wire pin spacing, but in four of the assemblies (K6A, K6B, AIR-1, and KO-1) the pins were centered in individual flow tubes by dimples in the flow tubes.

III. TEST EXPERIENCE

Table I presents some design and operating data for carbide fuel tests in the EBR-II. The tests having burnup goals of 12 at.% simulated the FFTF core midplane (peak power) conditions. The tests that simulated the top-of-core (peak cladding temperature) operating conditions have burnup goals of 8 at.%. All of the 7.87 mm diameter tests in the Type 316SS cladding reached the goals in burnup with no breaches, but those in the PE-16 cladding experienced breaches at about 5 to 6 at.% burnup. All but one of the completed 9.40 mm diameter tests in 316SS cladding also reached the goals in burnup with no breaches, but again, those in the PE-16 alloy did not. Breaches in the PE-16 cladding occurred in the helium-bonded pins at 4 to 6 at.% burnup and in the sodium-bonded pins at 8-11 at.% burnup. The one exception in the 316SS cladding was the K11 test. The K11 test pins were all sodium-bonded, about half had 316SS cladding, and the rest had PE-16 cladding. The K11 test was irradiated to 8 at.% burnup, was removed for examinations, and returned to the reactor. At about 10 at.% burnup, breaches occurred in two 316-clad pins. There is evidence that some K11 pins became partially unbonded during handling while the sodium bond was liquid, leading to higher fuel temperatures and accelerated fuel swelling. The K11 PE-16-clad pins were irradiated further to over 11 at.% burnup, and no breaches occurred, although there was evidence that some of these also may have been partially unbonded at the time of the interim examination. The reason for the difference in behavior between the two alloys after partial unbonding is not known, and no further investigation presently is planned. The sodium-bonded pins in PE-16 cladding achieved about twice the burnup of the helium-bonded pins in PE-16. The breaches in the PE-16 cladding are thought to be related to the low ductility of the material used.

After reaching the goals in burnup, pins of 6 of the tests were irradiated further. Fuel pins from the K6A, K6B, and AIR-1 tests were combined in one assembly for an overpower test (KO-1). These high-burnup pins were stablized for one hour at the same operating conditions as in their previous irradiations, and the power was then increased by 15% and held there for 10 minutes. The assembly was removed and the pins were examined. No significant effects of the overpower operation were detected. About half of the pins were replaced with high-burnup pins that had not experienced the overpower operation, and the irradiation was continued at normal power to learn the effects of the overpower operation upon the lifetime and performance of the pins. After about 4 at.% additional burnup a sodium-bonded pin breached at 15.8 at.% burnup. The breached pin had not experienced the overpower operation. The irradiation was continued with the sodium-bonded pins replaced with K6 helium-bonded pins. The test was recently removed from the reactor having achieved a peak burnup of 20.7 at.% (192 MWd/kg); no breaches occurred in the helium-bonded pins. The K7 test also was continued after goal burnup; a sodium-bonded pin breached at 13.1 at.%, but no breaches occurred in the helium-bonded pins through 17.1 at.% (158 MWd/kg) peak burnup. The K8 and K9 tests were examined upon reaching 4 at.% burnup and then were continued past their 8 at.% goal burnups until the subassembly hardware in each test reached the limiting swelled dimension. Both tests reached peak burnups over 12 at.% with no breaches in any of the pins. The peak fluence achieved in each of the four tests K6, K7, K8, and K9, was greater than 1.4×10^{23} n/cm^2 (E>1MeV).

The EC-series tests are high temperature (2σ) tests of type 316SS, D9, and D21 cladding. The EC-2 test has sodium-bonded pins having fuel shroud tubes, and the other four tests in this series are helium bonded. Breaches occurred in helium-bonded pins clad in the D21 alloy at about 4 at.% in the EC-1B and EC-3B tests, and, as a result, these two tests terminated. The breaches are thought to be the result of decreased ductility during irradiation in the D21 material used. Sodium-bonded pins in each of the three cladding alloys in the EC-2 test are over 6 at.% in peak burnup. There have been no breaches in the EC-2 test. The EC-1A and EC-3A tests include Type 316SS and D9 cladding. Some of the pins in the EC-1A tests have reached the goal burnup, 8 at.%, and the test will soon be complete. No breaches have occurred in the EC-1A test. In the EC-3A test, a breach occurred in a D9-clad, helium-bonded pin at 8.8 at.%. The test has resumed irradiation, and all of the continuing EC-3A D9 clad pins have burnups greater than 9.2 at.%. The EC-series breaches are discussed in a paper by Dr. R. L. Petty at this meeting.

IV. SUMMARY

The steady-state irradiation program of mixed-carbide fuels has demonstrated clearly the ability of carbide fuel pins to attain peak burnups greater than 12 at.% and peak fluences of 1.4×10^{23} n/cm^2 (E>0.1 MeV). Helium-bonded fuel pins in 316SS cladding have achieved peak burnups of 20.7 at.% (192 MWd/kg), and no breaches have occurred in pins of this design. Sodium-bonded fuel pins in 316SS cladding have achieved peak burnups of 15.8 at.% (146 MWd/kg).

Breaches have occurred in helium-bonded fuel pins in PE-16 cladding (~5 at.% burnup) and in D21 cladding (~4 at.% burnup). One breach has occurred in a helium-bonded high-temperature test in D9 cladding at 8.8 at.% burnup, but 10 pins of the same design in that test have achieved burnups in the range 9.2-9.9 at.% and are continuing in EBR-II.

Sodium-bonded fuel pins achieved burnups over 11 at.% in PE-16 cladding and over 6 at.% in D9 and D21 cladding. The test of the latter two alloys is continuing in EBR-II and is a high-temperature test. Sodium-bonded carbide pins clad in PE-16 and D21 have exhibited longer lifetimes than similarly clad helium-bonded carbide pins.

TABLE I
DESIGN AND OPERATING INFORMATION FOR CARBIDE FUEL PINS IN EBR-II

Design Parameters					Operating Parameters			As of 4/83
Test Series	Bond Type	No. of Pins	Smear Density (%T.D.)	Clad Type	Peak Power (kW/m)	Peak Clad Temp. (°C)	Goal Burnup (at.%)	Peak Burnup (at.%)/(MWd/kg)
				7.87-mm Diameter				
K6A	He	19	75-78	316 SS	72	565	12	12.1/111
K6B	He	19	78-81	316 SS	74	565	12	12.4/114
AIR-1	Na	19	81-83	316 SS	86	570	12	12.2/113
K7	He	13	75-81	316 SS	72	595	12	17.1/158
	Na	6	78	316 SS	78	595	12	13.1/122
K8	He	13	75-81	316 SS	48	650	8	12.8/118
	Na	6	78	316 SS	49	650	8	12.1/111
WSA 31	He	13	81-84	PE-16	84	595	12	6.4/59
WSA 34	He	19	75-84	PE-16	81	595	12	5.0/47
KO-1	He	13	75-81	316 SS	74	583	-	20.7/192
	Na	6	82	316 SS	79	580	-	15.8/146
				9.40 mm Diameter				
K9	Na	7	82	316 SS	73	655	8	11.8/109
	He	12	75-81	316 SS	72	655	8	12.5/115
K10	He	10	82-83	PE-16	78	655	8	5.7/53
		9	81	316 SS	78	655	8	8.8/81
K11	Na	9	81	PE-16	104	595	12	11.2/104
		10	81	316 SS	99	595	12	10.6/98
K12	Na	19	81-86	PE-16	98	595	12	11.7/108
WSA 32	He	19	75-82	316 SS	107	595	12	12.2/113
WSA 33	He	16	81-84	PE-16	128	595	12	4.0/37
		3	81	316 SS	115	595	12	4.1/38
EC 1A	He	5	78	316 SS	69	693	8	8.0/74
		11	78	D9	69	693	8	8.2/74
EC 1B	He	9	78	D9	69	693	8	3.8/35
		7	78	D21	69	693	8	3.8/35
EC 2	Na	4	81	316 SS	69	693	8	6.5/60
		6	81	D21	69	693	8	6.4/59
		6	81	D9	69	693	8	6.5/60
EC 3A	He	5	78	316 SS	98	670	12	9.7/90
		11	77-80	D9	98	670	12	9.9/92
EC 3B	He	8	78	D9	98	670	12	3.8/35
		8	78	D21	98	670	12	3.8/36